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Measurement of Impulse Peak Insertion Loss from two Acoustic Test Fixtures and Four Hearing Protector Conditions with an Acoustic Shock Tube

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Abstract

Impulse peak insertion loss (IPIL) was studied with two acoustic test fixtures and four hearing protector conditions at the EARCAL Laboratory. IPIL is the difference between the maximum estimated pressure for the open-ear condition and the maximum pressure measured when a hearing protector is placed on an acoustic test fixture (ATF). Two models of an ATF manufactured by the French German Research Institute of Saint Louis (ISL) were evaluated with high-level acoustic impulses created by an acoustic shock tube at levels of 134, 150, and 168 decibels (dB). The fixtures were identical except that the EARCAL ISL fixture had ear canals that were 3 mm longer than the NIOSH ISL fixture. Four hearing protection conditions were tested: Combat Arms earplug with the valve open, ETYPlugs® earplug, TacticalPro headset, and a dual-protector ETYPlugs earplug with TacticalPro earmuff. The IPILs measured for E-A-RCAL fixture were 1.4 dB greater than the NIOSH ISL ATF. For the E-A-RCAL ISL ATF, the left ear IPILs were 2.0 dB greater than the right ear IPILs. For the NIOSH ATF, the right ear IPILs were 0.3 dB more than the left IPILs.

I. INTRODUCTION

High-level, short-duration impulses present a greater risk of noise induced hearing loss than continuous noise of similar equivalent energy levels [1, 2, 3, 4, 5]. Hearing protection

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devices (HPDs) attenuate and filter an impulse and are integral to damage risk criteria and occupational safety and health standards [6, 7, 8]. Human subjects cannot ethically be used to assess HPD performance with high-level impulse noise due to the risk of inducing a threshold shift in the event that the protection fails to work as expected. Acoustic test fixtures (ATFs) have been used to measure insertion loss of hearing protection devices over a wide range of impulse levels, 110 to 190 decibels peak sound pressure level (dB peak SPL)[9, 10, 11, 12, 13].

The U.S. Environmental Protection Agency (EPA) recently proposed a new metric to characterize the performance of hearing protection devices in high-level impulse noise [14]. The EPA's methods evaluate a protector's performance at nominal impulse levels of 132, 150, and 168 dB peak SPL. The peak levels are allowed to vary from target levels within a range of _2 dB, and the initial overpressure (A-duration) can vary between 0.5 and 2.0 milliseconds (ms). The American National Standards Institute Subcommittee 12 (Noise) Working Group 11 subsequently revised the ANSI S12.42 standard using the EPA methods [15].

In previous field studies, NIOSH personnel evaluated different ATFs, hearing protectors, and impulse noise sources [16], [11]. The purpose of this study, performed at the 3M. E-A-RCAL Laboratory (Indianapolis, IN), was to utilize a more controlled laboratory environment to investigate the impulse peak insertion loss (IPIL) performance of a variety of protectors. Comparative measurements of the performance of hearing protectors with an ATF are useful for the development of national and international standards, as well, the methods in the ANSI/ASA S12.42 standard are still being refined to understand the assessment of hearing protection when exposed to high-level impulse noise.

This study utilized two models of the same ATF to measure the impulsive response of four hearing protector conditions. This paper reports and compares the measurements obtained with both fixtures. Section II describes the construction of the test fixtures, the acoustic impulse source, the hearing protectors used, as well as the data acquisition system and analysis methods. In Section III, the impulse waveforms are described, the results for each of the hearing protector conditions and the statistical analysis are presented. In Section IV, the effects of the fixture position, ear canal length and the performance of double protection are discussed.

II. METHODS

A. Acoustic Test Fixtures

NIOSH and 3M E-A-RCAL both purchased acoustic test fixtures from the French-German Research Institute of Saint Louis (ISL) built following the publication of the ANSI/ASA S12.42-2010 standard. The ISL fixtures were selected to facilitate comparison to previously published results collected with the ISL fixtures [9, 10, 12].

The length of the ear canals is a combination of an ear canal extension and the ear simulator to which the extension is attached [17, 15]. The ear canal extensions for the NIOSH ISL fixture were 13 mm long and had an inner diameter of 7.5 mm. The ear canal extensions for the E-A-RCAL ISL fixture were 16 mm long with a diameter of 7.5 mm. Due to the design of the ISL fixture, changes to the length of the ear canal extensions are difficult to make once the fixture is built. The ear canals, pinnae, and area surrounding the pinnae were flexible and had a Shore OO durometer rating of 75 to 76 when at room temperature or when heated to body temperature 37 °C. The pinna material was stiffer than the standard's specification of a durometer rating between 30 and 60.

Both fixtures were equipped with G.R.A.S. Sound & Vibration (GRAS) RA0045-S7 ear simulators, a modification of the IEC 60318-4 ear simulator. Each ear simulator was equipped with a 1/4” GRAS Type 40BP microphone and GRAS Type 26AC microphone preamplifier and was powered by a GRAS Type 12AA power module. A GRAS 67SB blast probe was used to measure the free field impulses. The blast probe was equipped with a GRAS 1/8” Type 40DP microphone and GRAS Type 26AC microphone preamplifier and was powered with a GRAS Type 12AA power module. The positions of the blast probe and ATFs are depicted in Figure 1.

B. Acoustic Impulse Source

An acoustic shock tube designed and developed by NIOSH generated the acoustic impulses for this study [18]. The overall dimensions of the shock tube apparatus were approximately 1.57 meters (62 in) long, 1.30 m (51 in) high, and 0.41 m (16 in) wide. The shock tube pressure chamber was a cylindrical steel tube, sealed on one end, approximately 0.81 m (32 in) long with an outer diameter of 0.10 m (4 in). The exhaust tube was 0.57 m (22.25 in) long. Polyester films of 0.127, 0.254 and 0.762 mm (0.5, 1.0, and 3.0 mil) in thickness were clamped between flanges to seal the pressure chamber. The chamber was pressurized with air and a trigger activated a lance to burst the membrane. A shock wave formed in the exhaust tube as the sudden release of compressed air propagated along the tube and into a catenoidal acoustic horn approximately 2.0 m (79 in) long with a square cross section, 1.10 by 1.10 m (43 by 43 in)[18]. The horn provided impedance matching between the exhaust tube and the room. The horn also eliminated a downstream flow-induced turbulent vortex, when the horn was absent and the chamber pressures were greater than about 137.9 kPa (20 pounds per square inch gauge, psig). In this study, the 134-dB impulses were generated with 0.5-mil polyester films at 30.3 kPa (4.4 psig). The 150 dB impulses were generated with 1-mil polyester films at 75.8 kPa (11 psig). The 168 dB impulses were generated with 3-mil polyester films at 374.1 kPa (47 psig).

Each sample of the different models of hearing protectors was fit on the ATF twice and one impulse was recorded per fitting. The unoccluded conditions were recorded at the beginning and end of the sequence of levels. For instance, three impulses of 132-dB unoccluded were followed by the tests for the 132-dB level for occluded conditions all of the samples of a given hearing protector model. Afterwards, another three unoccluded impulses at 132-dB were recorded. The same sequence of unoccluded-occluded-unoccluded conditions was completed for the 150-dB and 168-dB impulse levels. Each protector had five samples that were used during the testing. The details of protectors are described below.

C. Data Acquisition System

A National Instruments (NI) PXI data acquisition chassis was used with two NI PXI-4462 boards with four input channels, 24-bit resolution, 42 Volts input range, and 102.4 kHz sampling rate. The acoustic pressure data in Pascals were saved in a structured MATLAB .mat binary file for post-processing. One-second samples from five channels were simultaneously recorded for each impulse. The pre-trigger interval was 0.1 second and was accurate to within about 5 milliseconds (ms). The blast probe was on Channel 1 and the left and right ears of the 3M E-A-RCAL ISL ATF were connected to Channels 2 and 3, respectively. The left and right ears of the NIOSH ISL ATF were connected to Channels 4 and 5.

D. Equipment Setup

A reference point in the center of the mouth of the horn was defined by the intersection of a pair of strings stretched between the opposite corners of the horn's square face. The blast probe was positioned 1.02 meters from the reference point. The E-A-RCAL and NIOSH ISL ATFs were positioned 1.13 and 1.20 meters from the reference point, respectively. A laser line was used to sight along the sagittal seam of each fixture to the reference point. The fixtures and blast probe were not moved during the study since the impulse levels could be achieved by changing membranes and shock tube pressures. Unoccluded ear impulse levels of the E-A-RCAL ISL fixture were 1 to 2 decibels greater than the NIOSH ISL fixture, however the occluded measurements exhibited approximately the same levels across both fixtures. Prior to this study, the sensitivity of the results due to position and directionality with respect to the impulse source were unknown. Thus, a difference of 7 cm was not expected to be consequential.

The test fixture ear couplers were heated to approximately 37 °C, prior to calibration. The blast probe microphone was calibrated using a GR1462 adapter that clips onto the blast probe above the microphone. The ATF microphones were calibrated using the ISL ear canal adapter, eliminating the need to remove the pinnae.

E. Hearing Protection Devices

Three models of protectors were tested in this study: the 3M™ Single-Ended Combat Arms earplug with its filter open (Combat Arms), the Etymotic Research ETYPlugs® earplug (ETYPlugs), and the 3M. Peltor™ TacticalPro™ Communications Headset (Tactical-Pro). Figure 2 illustrates these protectors. All of the earmuffs and earplugs were fitted on the ATFs by the same researcher to ensure consistency in HPD fitting.

The Combat Arms earplug has a nonlinear acoustic filter that attenuates high levels while allowing low levels to pass through relatively unaffected. In the open-filter condition, this earplug's noise reduction rating (NRR) is 7 dB; in the closed- filter condition, the NRR is 23 dB. The ETYPlugs earplug provides a moderate level of attenuation and has an NRR of 16 dB. The TacticalPro earmuff is an electronic earmuff with an NRR of 26 dB. The TacticalPro earmuff was tested with its electronics set to unity gain by selecting the middle of five possible volume settings of the earmuff as recommended in the ANSI/ASA

S12.42-2010 standard. The dual combination of the ETYPlugs and electronic TacticalPro headset set at unity gain were tested as the fourth condition.

F. Data Analysis

The ANSI/ASA S12.42-2010 impulse signal analysis is summarized below. A unique transfer function, $H_{\mathrm{ATF-FF},L,n}(f)$, between the free-field (FF) microphone and the acoustic test fixture (ATF) exists for each impulse level and physical arrangement of the microphones and the impulse source. The transfer function between the field and the fixture microphones is described by

$$P_{ATF,L,n}(f)=H_{ATF-FF,L,n}(f)\times P_{FF,L,n}(f), \quad (1)$$

where $P_{\mathrm{FF},L,n}(f)$, and $P_{\mathrm{ATF},L,n}(f)$, are the discrete Fourier transforms of the free-field and ATF impulse waveforms, at a given level L and repetition number, n. For each test level, an average transfer function can be determined by dividing the Fourier transforms of the fixture and free-field impulses and averaging the result in the frequency domain across $N = 6$ unoccluded repetitions:

$$H_{ATF-FF,L}(f)=\frac{1}{N}\sum_{n=1}^{N}\frac{P_{ATF,L,n}(f)}{P_{FF,L,n}(f)} \quad (2)$$

This averaged transfer function is used to estimate the unoccluded fixture response for an occluded trial, from the impulse measured at the field microphone,

$$\mathrm{p}'_{ATF,L,i}(t)=FFT^{-1}\left(\mathrm{H}_{ATF-FF,\mathrm{L}}(f)\times \mathrm{P}'_{FF,L,i}(f)\right), \quad (3)$$

where $\mathrm{p}'_{ATF,L,i(t)}$ denotes the estimated unoccluded ATF pressure waveform, $\mathrm{P}'_{FF,L,i(\mathrm{f})}$ is the discrete Fourier transform of the free-field waveform for the same trial, and FFT^{-1} is the inverse discrete Fourier transform. The prime symbol on the pressures (e.g. p', P') indicates that the measurement was collected or calculated from an occluded measurement.

The IPIL is determined as the difference between the maximum absolute unoccluded and occluded peak sound pressure levels for the fixture, where L is the nominal peak level (134, 150, 168), i is the sample number, and j is the fitting number,

$$IPIL_{l,i,j}=20 \quad log_{10}\left(\frac{max_t\left|p'_{ATF,L,i,j}(t)\right|}{max_t\left|p_{ATF,L,i,j}(t)\right|}\right) \quad (4)$$

The $\mathrm{IPIL}_{(L,\,i,\,j)}$ are averaged for the two fittings (j = 1, 2) and then averaged over the five samples (i = 1, 2, ..., 5) to yield an average IPIL for each hearing protector device.

G. Statistical Model of Fixture Differences

A linear mixed effects model was developed determine if there were significant differences between the IPIL values measured in the right and left ears and the NIOSH and E-A-RCAL ISL fixtures. The outcome variable for the model was the IPIL value and the fixture, ear, and

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measured sound level were included as fixed explanatory variables. The random effects were the nominal impulse level, type of hearing protection device (nested within target noise level) and impulse number (nested within HPD). The data were analyzed using SAS's Proc Mixed and Stata's *mixed* command [19], [20] with the following model,

$$y_{ijklm}=\mu+\alpha_i+\beta_j+(\alpha\beta)_{ij}+\gamma x_{ijklm}+(\beta\gamma)_j x_{ijklm}+s_k+h_{l(k)}+p_{m(lk)}+\epsilon_{ijklm} \quad (5)$$

where y_{ijklm} = IPIL for ear *i*, fixture *j*, level *k*, HPD *l*, and impulse *m*;

μ = overall mean;

α_i = effect of ear *i* (left or right), i = 1, 2;

β_j = effect of fixture *j* (NIOSH or E-A-RCAL), j = 1, 2;

γ = coefficient for the effect of measured noise;

$(\alpha\beta)_{ij}$ = fixed effect of interaction between ear and fixture;

$(\beta\gamma)_j$ = interaction between fixed effects of fixture and of measured impulse level;

x_{ijklm} = measured impulse level for ear *i*, fixture *j*, level *k*, HPD *l*, and impulse *m*;

s_k = nominal sound level *k* (134, 150, 168), k = 1, 2, 3;

$h_{l(k)}$ = hearing protection device l = 1, 2, 3, 4;

$p_{m(lk)}$ = impulse number m = 1, 2...10;

ε_{ijklm} = error term for ear, fixture, level, HPD, and impulse.

Results

A. Waveforms

Examples of free-field impulse waveforms measured at the blast probe are shown in Figure 3. Impulses at the 168-dB and 150-dB levels had the sharp onset and trough that would be typical of an ideal Friedlander waveform. We experienced difficulties in utilizing the shock tube to create 132-dB impulses that exhibited a sharp onset impulse characteristic of a blast impulse. Consequently, the pressure was increased to yield impulses with sharper onsets and peak levels between 132 and 136 dB, 2 decibels more than the ANSI/ASA S12.42-2010 standard stipulates. For each range of impulse levels, the averages and standard deviations for the peak impulse levels measured by the blast probe are given in Table I.

When estimating the IPIL, the open ear transfer functions are calculated for each fixture, each ear and nominal impulse level. The peak gains presented in Table II depend upon the impulse level and example spectra for the blast probe and the included ears of the fixtures are presented in Figure 4. The blast probe impulses (solid line) exhibit a broad peak in the third octave band spectrum between 80 and 400 Hz. The 134 dB blast probe impulse spectra have an additional peak at 1000 Hz. The ear canal spectra have peaks at 3150 Hz at all levels due to the resonance of the ear simulator. Right ear spectra are dashed lines and left ear spectra are dotted-dashed lines. The greatest spectral content for the 168-dB impulses occur at 3150 Hz, whereas the 150 and 134-dB impulses have relatively more low-frequency content. The roll-off of the high frequency content for the 168-dB impulse was −3 dB/ octave, whereas the roll-off for the 150-dB and 134-dB impulse spectra was about −6 dB/ octave. The peak gains for right and left ears of the NIOSH ISL ATF are comparable and confirm that both ears were received approximately the same impulse levels. For the EARCAL fixture, the peak levels measured at the left ear were about 1 to 2 dB higher than those measured at the right ear. During the data collection, the fixtures were positioned to achieve the desired impulse levels and not moved given the limited time available to collect these data.

B. IPIL results for four HPD conditions

The IPIL results for each of the four hearing protector conditions are summarized in Table III. In general, the left ear IPIL results for the E-A-RCAL ISL fixture are the highest results for each of the protector conditions. The results for the right ear of the EARCAL ISL fixture are closer to the values measured for the right and left ears of the NIOSH ISL fixture.

1. 3M™ E-A-R™ Single-Ended Combat Arms Earplu—The IPIL results for the Combat Arms earplug individual test conditions ranged between about 7 and 12 dB for the 134-dB impulses, between 19 and 25 dB for the 150-dB impulses, and between 30 and 33 dB for the 168-dB impulses. Measurements of IPIL from the E-A-RCAL ISL ATF exhibited average differences between the left and right ears ($IPIL_{Left} – IPIL_{Right}$) of 1.4 dB for the 134-dB impulses, 2.0 dB for the 150-dB impulses and 3.2 dB for the 168-dB impulses. The average IPIL differences between the left and right ears of the NIOSH ISL fixture were −0.3 dB, −0.2 dB, and 0.7 dB for the 134, 150, and 168-dB impulses, respectively. The average IPIL differences between the two fixtures ($IPIL_{EARCAL} – IPIL_{NIOSH}$) were 1.9, 1.2, and 1.3 dB at the 134, 150, and 168-dB levels, respectively.

2. Etymotic Research ETYPlugs ® Earplug—The IPIL results for the ETYPlugs earplug ranged between about 12 and 18 dB for the 134-dB impulses, between about 15 and 21 dB for the 150-dB impulses and between about 26 and 30 dB for the 168-dB impulses. For the E-A-RCAL ISL ATF, the average IPIL differences between the left and right ears ($IPIL_{Left} – IPIL_{Right}$) were 1.3 dB for the 134-dB impulses, 1.7 dB for the 150-dB impulses and 1.1 dB for the 168-dB impulses. The average IPIL differences between the left and right ears of the NIOSH ISL ATF were −0.9 dB for the 134-dB impulses, −0.5 dB for the 150-dB impulses, and 0.3 dB for the 168-dB impulses. The average differences between two fixtures, ($IPIL_{EARCAL} – IPIL_{NIOSH}$), were 1.5, 1.8, and 1.5 dB at the 134, 150, 168-dB levels.

3. 3M™ Peltor™ TacticalPro Communications Headset—The IPIL results for the TacticalPro earmuff ranged between about 20 and 25 dB for the 134-dB impulses, between 27 and 31 dB for the 150-dB impulses, and between 37 and 41 dB for the 168-dB impulses. The IPIL differences between the right and left ears of the E-A-RCAL ISL fixture, ($IPIL_{Left}$ – $IPIL_{Right}$) were 1.5 dB, 1.4 dB, and 2.9 dB for the 134, 150 and 168-dB impulses. The average IPIL differences between the left and right ears of the NIOSH ISL ATF were -1.1 dB for the 134-dB impulses, −1.1 dB for the 150-dB impulses and 0.1 dB for the 168-dB impulses. The average IPIL differences between the E-A-RCAL and NIOSH ISL ATFs

($IPIL_{EARCAL}$ – $IPIL_{NIOSH}$) were 0.7 dB, 1.4 dB, 0.6 dB for the 134-dB, 150-dB, and 168-dB levels, respectively.

4. Dual protection ETYPlugs Earplug and TacticalPro Earmuff—The IPIL results for the dual protection combination test conditions ranged between about 28 and 32 dB for the 134-dB impulses, between 35 and 40 dB for the 150-dB impulses, and between 44 and 50 dB for the 168-dB impulses. For the E-A-RCAL ISL ATF, the average differences between left and right ears were 1.9 dB for the 134-dB impulses, 2.4 dB for the 150-dB impulses and 3.2 dB for the 168-dB impulses. The average IPIL differences between the left and right ears ($IPIL_{Left}$ – $IPIL_{Right}$) of the NIOSH ISL ATF were −1.0 dB for the 134-dB impulses, 0.3 dB for the 150-dB impulses and -1.1 dB for the 168-dB impulses. The average IPIL differences, ($IPIL_{EARCAL}$ – $IPIL_{NIOSH}$), were 1.0, 2.5, and 1.7 dB at the 134, 150, and 168-dB levels, respectively.

C. Level-dependent Attenuation

In Figure 5 the IPIL averages and standard deviations across samples and fittings of the different HPDs are plotted against the peak level of the impulse measured at the blast probe. The ETYPlugs, TacticalPro and combination of the ETYPlugs and TacticalPro exhibit similar amounts of gain as the impulse levels increase. The Combat Arms earplugs exhibited a greater slope, about 0.7 dB/dB, over the range of impulse levels than the other protectors, which exhibited about 0.4 to 0.5 dB/dB slope. The more rapid rise in the attenuation for the Combat Arms earplug can be attributed to the nonlinear filter that was designed to provide this response. The increases observed from the other products can be partly attributed to the increased high-frequency content of the impulse, which is more strongly attenuated by the response of the hearing protectors in the high frequencies. The TacticalPro earmuffs effectively function as a passive earmuff once the electronic pass-through and level-limiting circuits are shut down due to the high-level impulses.

D. Statistical Comparison of Fixtures

In Figure 5, three trends were observed. The IPIL values for the E-A-RCAL ISL fixture (open symbols and solid lines) were, on average, 1.4 dB higher than the values for the NIOSH ISL fixture (filled symbols and dotted lines) with a 95% confidence interval of (1.2, 1.5) dB. The difference was statistically significant at $p < 0.001$. The left ear IPIL results from the E-A-RCAL ISL fixture were greater than the right ear IPIL results by 2.0 dB with a 95% confidence interval of (2.2, 1.8) dB. For the NIOSH ISL fixture, the opposite trend occurred, the left ear IPIL results were slightly less than the right ear results, −0.3 dB with a 95% confidence interval of (−0.1, −0.6) dB. These trends were quantified across the four protector conditions by the statistical model described Section II G.

1. Interaction effects—The statistical model evaluated the interactions between the fixture and the ear and between the interaction of impulse noise level and the fixture. Table IV shows that the fixtures were not significantly different when the interaction term for impulse noise level and fixture was included in the model. The differences between slopes of the IPILs measured from both fixtures were not significant. However, the differences for the IPIL measured for the right and left ears within a fixture were statistically significant; the

IPILs exhibited a consistent trend for the right and left ears. Because the interaction term between the fixture and ear was statistically significant, the right/left ear differences on the E-A-RCAL fixture were not the same as those measured for the NIOSH fixture. The right/left ear differences can be readily observed in Figure 5, as can the similarity of the increase in IPIL with impulse noise level.

2. Least squares means of the residuals

A comparison of the least squares means of the residuals by protector was conducted using Levene's method. In Table V, the Combat Arms earplug had the lowest residual variance. The ETYPlugs had the second lowest followed by the TacticalPro. The dual protector combination had the largest residual variance. The differences between residual variance between the hearing protector conditions were compared. The single protector comparisons (TacticalPro/ETYPlug, TacticalPro/Combat Arms, and ETYPlug/Combat Arms) were not statistically significant. The confidence intervals of the least squares mean residuals for the Combat Arms (0.36, 0.57) overlaps the confidence interval for the TacticalPro (0.51, 0.72). The residual difference for the dual protector condition was also not statistically significant compared to the TacticalPro. However for the dual protector combination and both of the earplugs, the confidence intervals do not overlap and the differences between residual least squares means were statistically significant ($p < 0.0001$).

IV. DISCUSSION

A. Fixture Position

The differences between the IPIL values measured for the fixtures may have been caused by the physical arrangement of the fixtures. The E-A-RCAL ISL fixture was 7 cm closer to the mouth of the horn and received impulse levels between 0.6 and 3.0 dB higher than the NIOSH ISL fixture, based upon the unoccluded calibration impulse levels at the open ear (See Table II and Figure 4). The fixtures were aimed at the reference point in the center of the mouth of the horn; the differences between left and right ears were the result of baffle and head shadow effects. The left ear of the E-A-RCAL ISL fixture was more exposed than the right ear as exhibited by the increased transfer function of the open ear. Because the left ear of the E-A-RCAL ISL fixture experienced peak impulses 2 to 3 dB greater than the left ear, thus the IPIL would be 1-2 dB more based upon the slope of the IPIL function. For the NIOSH ISL fixture, the IPILs from the right ear tended to be higher than those from the left ear. Although the peak impulse level right/left ear differences were smaller for the NIOSH ISL fixture, the trend was consistent with a baffle effect for the right ear and head shadow effect for the left ear.

The ANSI S12.42 standard describes the calculation of the expanded uncertainty for the IPIL measurement but does not detail comparison of results between test fixtures. Also, the ANSI standard conducts the measurements with grazing incidence, the mannequin facing the impulse source [15]. The MIL-STD 1474D conducts measurements with a fixture in normal incidence, which yields one ear facing the source and the other ear shadowed [7]. For the purpose of developing a rating and to achieve comparable data from the right and left ear microphones of the fixture, the grazing incidence condition was preferred.

Parmentier et al. positioned fixtures in grazing incidence at the same distance from an explosive charge for the testing conducted at the French German Research Institute of Saint Louis [12]. For a radially symmetric impulse source, the positioning is straightforward.

These data demonstrate that the position of the ATFs within the sound field produced by the shock tube had statistically significant effects upon the measured IPIL. The ATF's orientation matters. Although we endeavored to determine the aim of the fixtures before commencing all of the data collection, the full analysis could only be performed post hoc.

B. Ear Canal Length

The NIOSH ISL ATF was the first one constructed by ISL after the ANSI/ASA S12.42 (2010) standard was published and was designed to conform to the standard's requirements. The standard stipulates that the ear canal extension added to the coupler shall be 14±1 mm in length. The NIOSH ISL ATF ear canal extensions permitted earplug insertions of 13 mm. After the ear canal length was discussed with the designers, subsequent ISL test fixtures (including E-ARCAL's) were built with ear canal extensions that permitted about 16 mm of earplug insertion depth. Slightly longer ear canal extensions should yield higher IPIL estimates because more of the lateral surface of the earplug can be in contact with the walls of the ear canal extension. In general, the insertion depth is a critical factor for achieving an adequate amount of protection when exposed to continuous noise [19, 20]; therefore, it will be critical to providing protection from impulse noise.

In this study, premolded, triple-flanged earplugs were evaluated. The third flange (most lateral) made contact with the ear canal extension. This flange was larger than the diameter of the ear canal extension; therefore, the flange would wrinkle if it were inserted further into the canal. During testing, the plugs were inserted such that the third flange just made contact with the ear canal extension and was not wrinkled. Flanged earplugs fitted into a shorter ear canal do not contact with the lateral end of the ear canal [21, 11].

C. Effect of Source Spectrum on IPIL

The IPIL is affected by both the source spectrum and the attenuation spectrum of the hearing protection device. From Figure 4, the high-frequency contribution in the open ear condition for the 168-dB impulses was significantly greater than broad, low frequency peak. The high-frequency enhancement comes from the resonance of the ear canal and ear simulator. The high-frequency components at the 150-dB and 134-dB impulse levels are comparable to or less than the broad low-frequency peak.

As reported in Section III C, the slope for the growth of IPIL with impulse level for the Combat Arms earplug in the open valve mode was 0.72 dB/dB. The slopes for the growth of IPIL with impulse level for the ETYPlugs were 0.40 dB/dB and 0.45 dB/dB for the TacticalPro earmuffs. Murphy et al. [11] measured IPIL for the Combat Arms earplug using a Colt AR-15 0.223 caliber rifle as the impulse source and the slope derived from their data was 0.26 dB/dB. Similarly for the ETYPlugs and TacticalPro, Murphy et al. [22] reported IPIL using a Colt AR-15 . 223 caliber rifle impulse source and the derived slopes were 0.22 dB/dB for the ETYPlug and 0.45 dB/dB for the TacticalPro. These values are of interest because the sharp onset of the impulse for the rifle-generated impulse was maintained across the range of investigation. Because high-frequency content was maintained, less of a change in IPIL was observed as the impulse level was changed.

Hamernik and Hsueh [23] examined a Friedlander waveform with an instantaneous and a finite rise time. The finite rise time waveform spectrum at high frequencies exhibited a significantly greater decay with increasing frequency than for the case where the blast wavefront transition is instantaneous. They further examined the effect of A-weighting on the energy flux and demonstrated the relative effect of the transfer function of the open ear, the A-weighting curve, on the low-frequency components of the impulse. The A-weighting curve could be considered as a surrogate for a hearing protector since the spectrum varies with frequency. When the greatest spectral content coincides with the lowest attenuation, an enhanced level of transmission is observed. Spectral information is not an outcome variable of the IPIL method, however, Figure 4 demonstrates how the IPIL can be affected by the spectral content. Greater high frequency content coupled with more passive attenuation capacity at high frequencies will yield an increased IPIL value [24].

D. Improvements for the ANSI S12.42 Standard

Several aspects of the ANSI S12.42 standard need to be reconsidered following this investigation. The original intent of the impulse noise portion of the standard was to provide a simple method to distinguish between performances of hearing protection devices in the presence of high-level impulse noises. The standard has been successful with respect to rank ordering the performance of various protectors. For passive linear hearing protectors such as earplugs, semi-aural insert devices or earmuffs, the Noise Reduction Rating can be expected to provide a high degree of correlation with the IPIL [25, 11]. Although this paper does not consider the performance of multiple impulse sources used to evaluate the same protector, Murphy et al. found that the IPIL is considerably greater when a rifle was used as the impulse noise source versus the acoustic shock tube [24]. Thus, the ANSI S12.42 standard needs to specify the spectrum of the impulse noise source used to measure IPIL. Preliminary investigations suggest that the insertion loss spectrum for a particular model of hearing protector will exhibit a more consistent comparison than the IPIL as defined by the standard [24].

The comparison of results from different sources and fixtures will continue to be a challenge. One means to facilitate the comparison between identical fixtures but different impulse levels would be to adjust the peak level of the impulse by the unoccluded level measured at the ear. In Figure 6 the IPIL data are plotted with an adjustment for the increased impulse level from the unoccluded ear. The higher impulse levels at the EARCAL ISL fixture's left ear are moved to the right on the graph and improve the agreement between the two fixtures. The ANSI S12.42 standard specified three impulse test levels: 132, 150 and 168 dB. Because IPIL changes in a continuous manner as a function of the peak pressure of the impulse waveform, the number of impulse test levels could be increased to better capture the change in IPIL as a function of level. The comparisons between tests from studies separated in time or at different facilities that utilize spectrally similar impulse sources may benefit from having more tests across the range of impulses between 130 and 170 dB peak SPL.

Although bone conduction was not considered in this paper, the measured IPIL values for the dual protection condition exceed the lowest limit of 41 dB at 2000 Hz published in the standard [15]. The standard does not describe how to account for bone conduction. New test fixtures could be designed to incorporate a bone conduction limit that has a similar response to the human cranium. Research needs to be conducted to account for both the attenuation and phase changes introduced by bone conduction in order to modify the measured signals transmitted through the protector to the ear simulator.

E. Implications for Hearing Conservation

The IPIL describes the performance of hearing protection devices in high-level impulse noise. The NRR describes the performance of hearing protection devices in continuous noise. Because IPIL is measured with an acoustic test fixture, it should be more repeatable and a more sensitive performance measure than the NRR due to the lack of anatomical differences of the head and ear canal. For the NRR, within-subject standard deviation of attenuations measured by real ear attenuation at threshold (REAT) are about 0.2 to 0.4 dB for earmuffs and 0.3 to 0.6 dB for earplugs [19]. These standard deviations were comparable to what was observed in this study for the IPIL values listed in Table III. However, differences of 3 decibels or more are usually the benchmark of practical significance when comparing the NRRs of two REAT tests of the same protector with different subject panels [20]. Smaller statistically significant differences can be identified for the IPIL than what might be measurable for NRR. Thus, the IPIL test is useful for purposes of refining the design of particular features of a protector when used in high-level impulse noise. Practically, how the user wears the hearing protector will dramatically affect the protection s/he might expect to receive.

V. CONCLUSIONS

Statistically significant differences were observed between the IPILs measured for the right and left ears of the two fixtures evaluated in this study. Although the two fixtures have ear canals of different lengths, the IPILs should have been the same for our premolded earplugs so long as the plugs were inserted to the same depth and the earmuffs similarly fitted on the fixture. For foam earplugs, the additional ear canal length would be expected to increase the measured IPIL values. The baffle and head shadow effects are cited as the main reason for the discrepancy between ears. Differences in the average levels observed with the NIOSH and E-A-RCAL ISL fixtures can be attributed to the positions of the fixtures in the sound field. These differences suggest that the IPIL is sensitive to small changes in measurement conditions for the fixtures and in impulse levels. While the observed differences between the right and left ears of the two fixtures were statistically significant, the utility of the IPIL measurement provides a means to compare protector performance across a wide range of products. Future studies will continue to refine our understanding of hearing protector performance in impulse noise and how it can be measured to predict exposures and prevent hearing loss.

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References

1. Coles, RR.; Garinther, GR.; Hodge, DC.; Rice, CR. Technical Report AMCMS Code 5011.11.84100. Human Engineering Laboratories; Aberdeen Proving Ground, MD: 1967. U.S. Army Technical Memorandum 13-67 Criteria for Assessing Hearing Damage Risk from Impulse-Noise Exposure..
2. Dancer A, Franke R. Hearing Hazard from Impulse Noise: A Comparative Study of Two Classical Criteria for Weapon Noises (Pfander Criterion and Smoorenburg Criterion) and the L_{Aeq8} Method. Acta Acustica. 1995; 3:539–547.
3. Dunn DE, Davis RR, Merry CJ, Franks JR. Hearing loss in the chinchilla from impact and continuous noise exposure. J. Acoust. Soc. Am. 1991; 90(1):1979–1985. [PubMed: 1669963]
4. Hamernik, RP.; Patterson, JH.; Ahroon, WA. Final Report DAMD17-96-C-6007. State University of New York; Plattsburgh, NY: 1998. Use of animal test data in the development of a human auditory hazard criterion for impulse noise..
5. Henderson, D.; Hamernik, RP. Auditory Hazards of Impulse and Impact Noise. In: Crocker, MJ., editor. Chapter 27 in Handbook of Noise and Vibration Control. John Wiley & Sons; 2007. p. 326-336.
6. Direction Technique de Armements Terrestres. Technical Report AT-83/27/28. Establissement Technique de Bourges; 1983. Recommendations on evaluating the possible harmful effects of noise on hearing..
7. MIL-STD 1474D. Department of Defense Design Criteria Standard, Noise Limits. Department of Defense; Washington DC: 1997.
8. OSHA. CPL 2-2.35A-29 CFR 1910.95(b)(1) Guidelines for noise enforcement: Appendix A. U.S. Department of Labor, Occupational Safety and Health Administration; Dec 19. 1983 1983
9. Berger, EH.; Hamery, P. Acoustics '08. Acoustical Society of America; Paris: Jul. 2008 Empirical evaluation using impulse noise of level-dependency for passive earplug designs.. 2008
10. Murphy WJ, Tubbs RL. Assessment of noise exposure for indoor and outdoor firing ranges. J. Occ. Env. Hyg. 2007; 4:688–697. 2007.
11. Murphy WJ, Flamme GA, Meinke DK, Søndergaard J, Finan DS, Lankford JE, Khan A, Vernon J, Stewart M. Measurement of impulse peak insertion loss for four hearing protectors in field conditions. Int. J. Aud. 2012; 51:S31–S42. 2012.
12. Parmentier G, Dancer A, Buck K, Kronenberger G, Beck C. Artificial Head (ATF) for Evaluation of Hearing Protectors. Acustica. 2000; 86:847–852.
13. Zera J, Mlynski R. Attenuation of high-level impulses by earmuffs. J. Acoust. Soc. Am. 2007; 122:2082–2096. [PubMed: 17902846]
14. EPA. 40 CFR 211B Hearing Protective Devices Product Noise Labeling Hearing Protection Devices; Proposed Rule. U.S. Environmental Protection Agency; Washington D.C.: Aug 5. 2009 2009
15. ANSI/ASA S12.42. American National Standard Methods for the Measurement of Insertion Loss of Hearing Protection Devices in Continuous or Impulsive Noise Using Microphone-in-Real-Ear or Acoustic Test Fixture Procedures. American National Standards Institute; New York: 2010.
16. Murphy WJ, Flamme GA, Meinke DK, Finan DS, Lankford JE, Khan A, Søndergaard J, Stewart M. Comparison of three acoustic test fixtures for impulse peak insertion loss. J. Acoust. Soc. Am. 2011; 130
17. ANSI/ASA S3.25. American National Standard for an Occluded Ear Simulator. American National Standards Institute; New York: 2014.

18. Khan, A.; Murphy, WJ.; Zechmann, EL. Survey Report EPHB 350-12a. National Institute for Occupational Safety and Health; Cincinnati, OH: 2012. Design and construction of an acoustic shock tube for generating high-level impulses to test hearing protection devices..

19. Murphy WJ, Byrne DC, Gauger D, Ahroon WA, Berger EH, Gerges SNY, McKinley RL, Witt B, Krieg EF. Results of the National Institute for Occupational Safety and Health-U.S. Environmental Protection Agency interlaboratory comparison of American National Standards Institute S12.6-1997 Methods A and B. J. Acoust. Soc. Am. 2009; 125:3262–3277. [PubMed: 19425669]

20. Murphy WJ, Stephenson MR, Byrne DC, Witt B, Duran J. Effects of training on hearing protector attenuation. Noise and Health. 2011b; 13:132–41. [PubMed: 21368438]

21. Murphy, WJ. NIOSH/NHCA Best Practices Workshop on Impulsive Noise and Its Effects on Hearing. NIOSH; Cincinnati, OH: 2003. Peak reductions of nonlinear hearing protection devices..

22. Murphy, WJ.; Fackler, CJ.; Shaw, PB.; Khan, A.; Meinke, DK.; Finan, DS.; Lankford, JE.; Stewart, M. Survey Report EPHB 350-14a. National Institute for Occupational Safety and Health; Cincinnati, OH: 2015. Comparison of the Performances of Three Acoustic test Fixtures Using Impulse Peak Insertion Loss Measurements..

23. Hamernik RP, Hsueh KD. Impulse noise: Some definitions, physical acoustics and other considerations. J. Acoust. Soc. Am. 1991; 90(1):189–196. [PubMed: 1880288]

24. Murphy WJ, Berger EH, Ahroon WA. Comparison of impulse peak insertion loss measured with gunshot and shock tube noise sources. J. Acoust. Soc. Am. 2014; 136(4):2165. 2014.

25. Meinke, DK.; Murphy, WJ.; Flamme, GA.; Finan, DS.; Lankford, J.; Khan, A.; Vernon, JA.; Stewart, M. AudiologyNow!. Boston MA: Mar 28-31. 2012 Measurement of Impulse Peak Insertion Loss for Four Hearing Protectors.. 2012

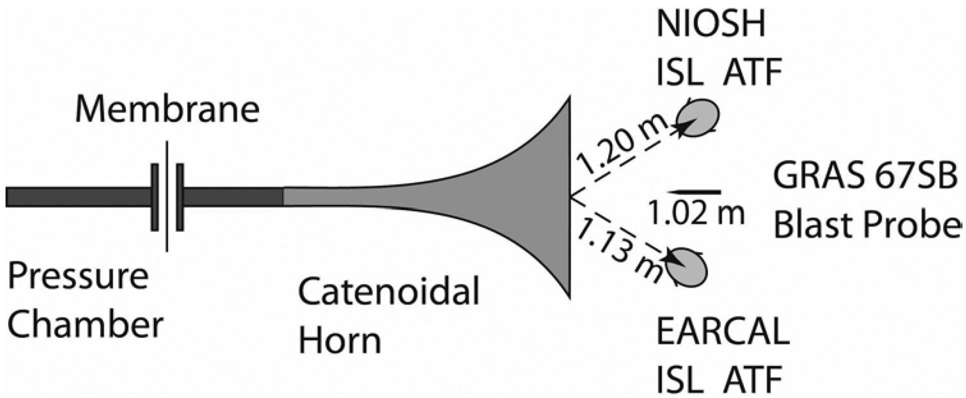

Figure 1.

Schematic arrangement of the acoustic shock tube, catenoidal horn, acoustic test fixtures and the blast probe. The fixtures were sited along the sagittal seam of the fixture to point to the center of the mouth of the catenoidal horn. The E-A-RCAL, NIOSH ISL fixtures were 1.13 and 1.20 m from the reference point, respectively. The GRAS 67SB blast probe was 1.02 m from the reference point. (Color online)

Figure 2.

The three models of hearing protectors tested in this field study. The 3M™ E-A-R™ Single-Ended Combat Arms™ Earplug has a toggle that was opened during testing. The Etymotic Research ETYPlugs® Earplug was tested as is. The 3M™ Peltor™ TacticalPro Communications Headset was tested with electronics on and set to unity gain. The double protector combination of the ETYPlugs earplug and TacticalPro earmuff was also tested. (Color online)

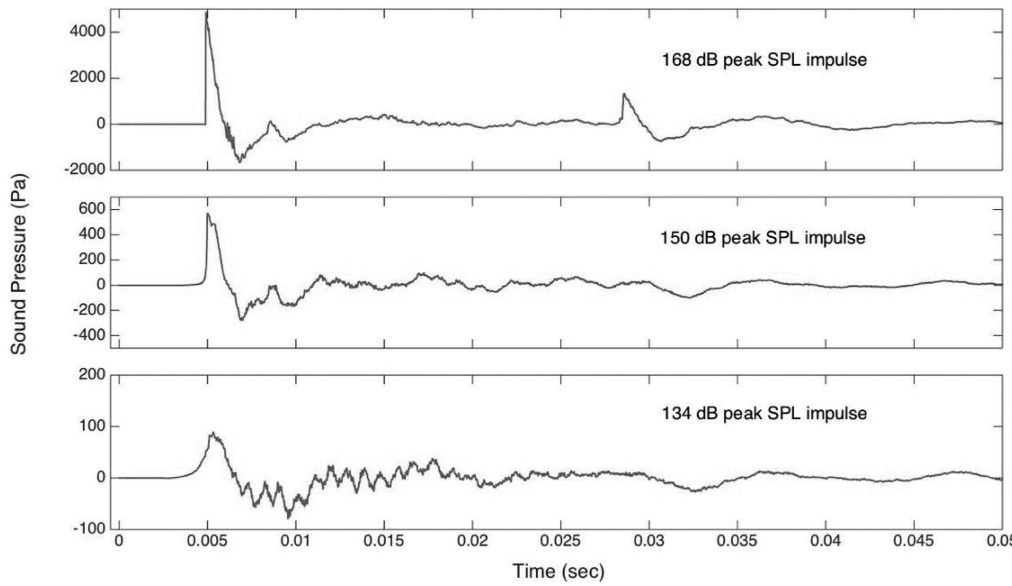

Figure 3.
The unoccluded waveforms for the impulses measured at the blast probe at the three impulse levels. At about 23 ms after the initial impulse, the 168 impulses exhibit a strong secondary impulse created when the impulse reflects from the mouth of the horn and back end of the pressure chamber.

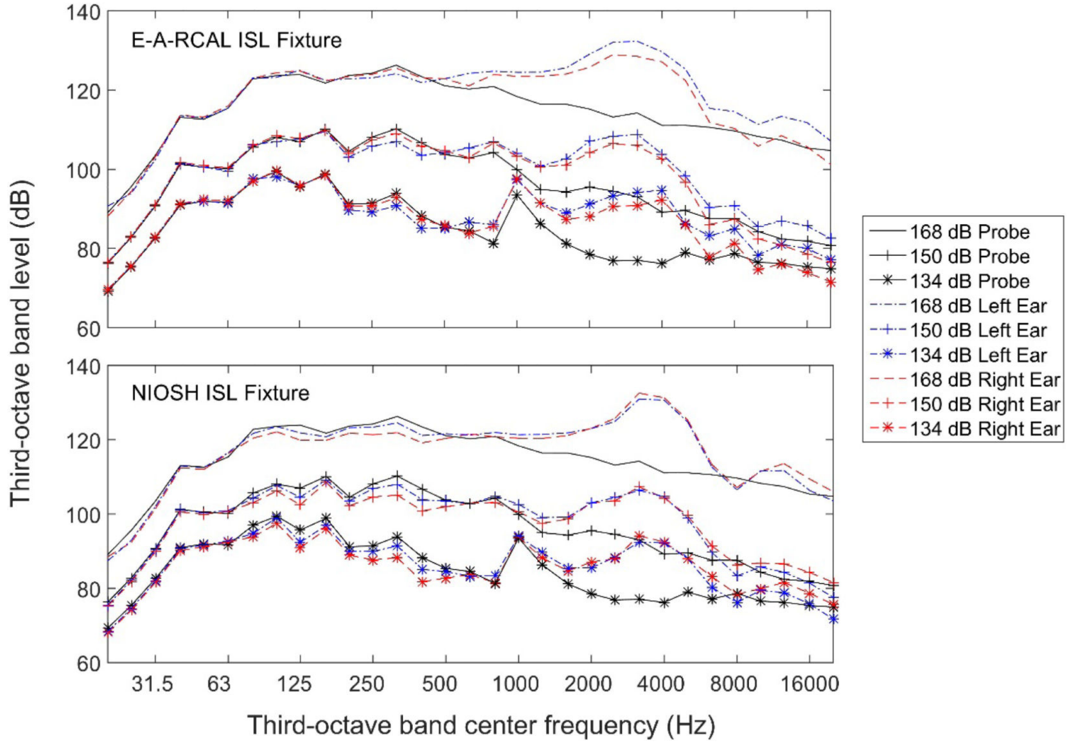

Figure 4.

The unoccluded spectra of the impulses measured at the blast probe and by the fixture microphones at the three impulse levels. The 134-dB impulses are indicated by * symbols; the 150-dB impulses are indicated by + symbols; the lines without symbols are the 168-dB impulses. The blast probe is indicated by the solid line, right ear by the dashed line and the left ear of the fixtures by dotted-dashed line. The transfer function of the open ear is slightly higher for the left ear of the EARCAL fixture than it is for the right ear of the fixture. The right and left ears of the NIOSH fixture exhibit the same transfer function. (Color online)

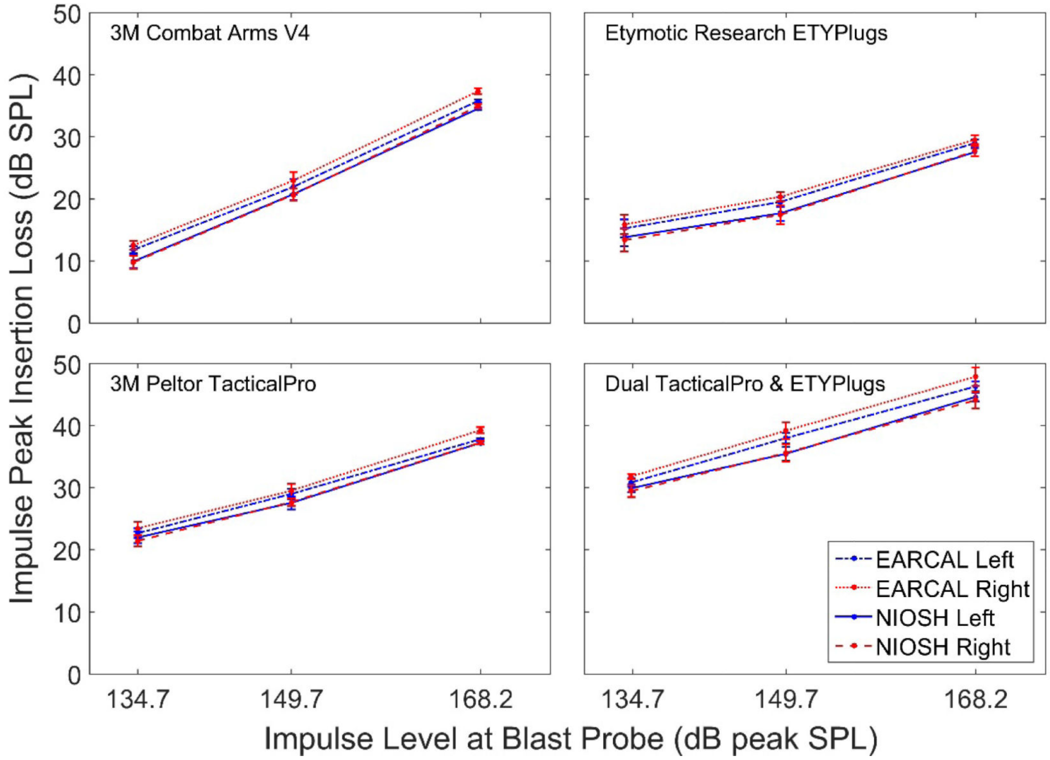

Figure 5.

Average IPIL results versus average peak impulse level measured at the blast probe. The E-A-RCAL ISL fixture IPIL data are plotted for the left ear (dashed-dotted line) and right ear (dotted line). The NIOSH ISL fixture IPIL data are plotted for the left ear (solid line) and the right ear (dashed line). The right and left ear data from the NIOSH ISL fixture exhibit close agreement, whereas the left ear IPIL of the E-A-RCAL ISL fixture are consistently greater than the right ear IPIL data. (Color online)

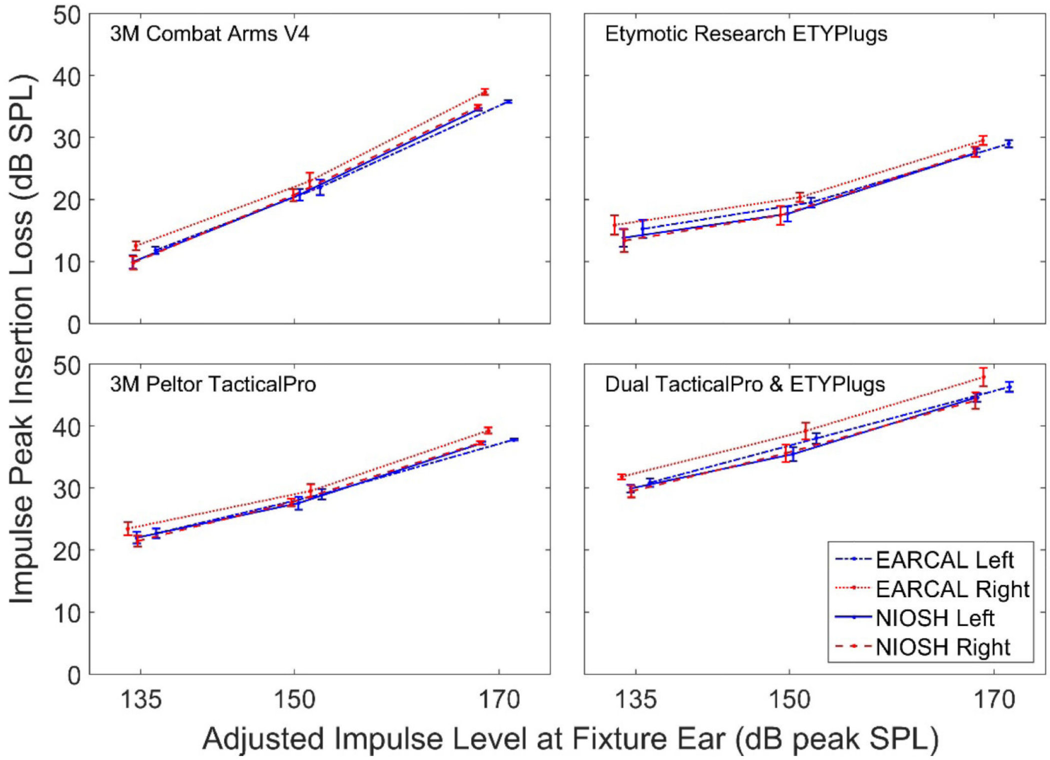

Figure 6.

The IPIL results versus average adjusted peak impulse level at the ear of the test fixture. The E-A-RCAL ISL fixture IPIL data are plotted for the left ear (dashed-dotted line) and right ear (dotted line). The NIOSH ISL fixture IPIL data are plotted for the left ear (solid line) and the right ear (dashed line). The impulse levels against which the data are plotted have been adjusted by the difference in the unoccluded peak level measured at the ear of the fixture relative to the right ear of the NIOSH ISL fixture. (Color online)

Table I

Average peak impulse levels and standard deviations (dB peak SPL) measured by the blast probe for the ten impulses used to assess IPIL of each protector condition.

Protector	Averaged	Peak Impulse	Levels (dB)
Combat Arms	167.9±0.2	149.9±0.9	134.3±1.4
ETYPlugs	168.1±0.2	149.1±0.9	133.9±1.0
TacticalPro	168.2±0.2	149.7±0.9	134.7±0.9
TacticalPro and ETYPlugs	168.2±0.3	149.7±0.5	134.6±0.4

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Table II

The increase in the peak impulse level relative to the blast probe for each fixture, ear and level. The blast probe peak sound pressure levels were subtracted from the unoccluded peak levels for each fixture, ear and nominal pressure level to estimate the gain for the transfer function of the open ear.

Peak gain of the transfer function of the open ear (dB)				
Fixture	**Ear**	**168**	**150**	**134**
E-A-RCAL	Left	12.0±0.2	5.4±0.6	3.5±0.8
E-A-RCAL	Right	9.6±0.2	4.5±0.6	2.4±0.8
NIOSH	Left	8.9±0.2	2.8±0.6	1.2±0.8
NIOSH	Right	8.8±0.2	2.0±0.5	1.0±0.9

Table III

Average peak impulse levels, IPIL and standard deviations from ten impulses and five samples for right, left and both ears of the E-A-RCAL and NIOSH ISL acoustic test fixtures of the four hearing protector conditions.

		E-A-RCAL ISL ATF			**NIOSH ISL ATF**		
Protector	Ear	168 dB	150 dB	134 dB	168 dB	150 dB	134 dB
	Left	37.4±0.5	23.0±1.3	12.5±1.2	34.9±0.3	20.7±1.0	9.8±1.4
Combat Arms	Right	34.2±0.4	21.0±1.2	11.1±0.9	34.2±0.3	20.9±1.0	10.1±1.4
	Average	35.8±0.3	22.0±1.2	11.8±1.0	34.5±0.2	20.8±1.0	9.9±1.4
	Left	29.5±0.7	20.4±1.1	15.9±1.6	27.7±0.8	17.4±1.6	13.4±1.9
ETYPlugs	Right	28.4±0.7	18.7±1.2	14.6±1.5	27.4±0.7	17.9±1.2	14.3±1.2
	Average	29.0±0.6	19.5±1.1	15.3±1.4	27.5±0.6	17.7±1.4	13.8±1.5
	Left	39.3±0.5	29.5±1.2	23.4±1.6	37.3±0.4	27.0±2.3	21.4±1.3
TacticalPro	Right	36.4±0.4	28.5±0.7	21.9±1.2	37.2±0.5	28.1±0.8	22.5±1.6
	Average	37.8±0.2	29.0±0.9	22.7±1.3	37.2±0.3	27.6±1.3	22.0±1.4
Dual	Left	47.9±1.5	39.2±1.5	31.8±0.6	44.1±1.3	35.6±1.5	29.4±1.0
ETYPlugs &	Right	44.7±0.6	36.8±0.8	29.9±1.4	45.2±0.7	35.3±1.5	30.4±0.9
TacticalPro	Average	46.3±0.8	38.0±1.0	30.9±0.8	44.6±0.7	35.5±1.2	29.9±0.8

Table IV

Tests of fixed effects between fixture and ear and level and fixture between the measured impulse noise.

Effect	F-Value	Pr > F
Fixture	3.32	0.0694
Ear	107.67	< 0.0001
Fixture * Ear	214.08	< 0.0001
Impulse Level	33.06	< 0.0001
Impulse Level * Fixture	0.05	0.8206

Table V

Least squares means of the residuals. The least squares means of the residuals for each protector condition was evaluated to understand the relative variance associated with fitting the protectors on the two fixtures

Protector	Least Squares Means Residual (dB)	95% Confidence Interval
Combat Arms earplug	0.46	(0.36, 0.57)
ETYPlugs earplug	0.56	(0.45, 0.67)
TacticalPro earmuff	0.61	(0.51, 0.72)
TacticalPro and ETYPlugs	0.79	(0.68, 0.89)